

Optical Metrology

for Wavelength-Division-Multiplexed Fiber Communications

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The rapid growth of high-bandwidth optical fiber communication systems has greatly increased the need for accurate measurement of spectral, polarization, and dispersion properties of optical fiber and components. Wavelength-division multiplexing (WDM) increases bandwidth by using many wavelength channels. Most systems employ 50 GHz (0.4 nm) or 100 GHz (0.8 nm) channel spacing in the 1540-1560 nm region, but narrower channel spacing may be implemented in the future. Systems will be implemented in other wavelength regions as well, possibly covering the entire range from about 1280 nm to 1630 nm.

WDM places requirements on wavelength stability, crosstalk, and polarization dependence of components such as wavelength channel filters and multiplexers. High bit-rate WDM systems have additional requirements: dispersion, the variation of propagation velocity with wavelength or polarization, sets a limit to the rate at which information can be transmitted. A variety of dispersion compensation methods are under development to manage dispersion in future systems. The Optical Components Group of the National Institute of Standards and Technology (NIST) develops and evaluates high resolution measurement techniques for these areas and also produces calibration references for wavelength, polarization dependent loss, and polarization-mode dispersion measurement. In this article, we will describe NIST's metrology efforts and current challenges in the areas of optical fiber and component characterization.

In response to rapid changes in fiber-optic technology, the Optoelectronics Division of the National Institute of Standards and Technology has been developing techniques and standards to support the measurement of optical components and subsystems used in wavelength-division-multiplexed optical fiber communication systems. Current projects include the development of wavelength calibration transfer standards and the accurate measurement of spectral response, dispersion, and polarization dependence of optical fiber and components.

Wavelength calibration

Instruments such as optical spectrum analyzers, tunable lasers, and wavelength meters are used to characterize WDM system components and measure channel wavelengths. Stable and accurately measured wavelength references can be used for single-point and scan-linearity wavelength calibration of these instruments. Atomic and molecular absorption lines provide wavelength references that are very stable under changing environmental conditions and have well

understood physical behavior. We have developed moderate accuracy (~ 0.1 -1 pm) transfer standards for the 1500 nm region that incorporate molecular gas absorption cells. These transfer standards are simple devices for calibrating instruments. We have also developed higher accuracy standards for NIST internal calibration based on high-resolution spectroscopy of methane and atomic rubidium.

Our moderate accuracy references are NIST Standard Reference Material (SRM) transfer standards based on rotational-vibrational transitions of acetylene, $^{12}\text{C}_2\text{H}_2$ (SRM 2517a), and hydrogen cyanide, $\text{H}^{13}\text{C}^{14}\text{N}$ (SRM 2519). Acetylene has more than 50 strong absorption lines in the 1510-1540 nm region,¹ and hydrogen cyanide (Fig. 1) has about 50 lines in the 1530-1565 nm region.² Although molecular structure is relatively insensitive to changes in environmental conditions, slight shifts of line centers can occur under certain conditions. The largest potential source of line shift—the pressure shift—takes place because of energy level shifts caused by the interaction of the molecules during collisions.

To provide sufficient signal when used with a 0.1 nm resolution instrument, the gases in the SRMs are at moderate pressures. We measured the pressure shift for both acetylene³ and hydrogen cyanide⁴ and found that the pressure shift is slightly different for each line, but is typically less than 1 pm for the SRM cell pressures. Since the cells have all-glass seals, this shift is very insensitive to the external environment.

The SRMs were designed for calibrating wavelength-measuring instruments such as optical spectrum analyzers and wavelength meters. The units are optical-fiber-coupled with single-mode fiber, and the spectrum can be observed using a broadband source—such as a light-emitting diode or amplified spontaneous emission source—or a tunable laser. Single-wavelength calibrations using a single line, and scan linearity measurements using multiple lines, can be made. NIST has evaluated the uncertainty of the line centers and provides certified wavelength values. Most of the lines are certified with an uncertainty of less than 1 pm, and some of the acetylene lines are certified with an uncertainty of 0.1 pm. Each SRM unit is measured at NIST to assure that it has sufficient purity and contains the correct gas pressure.

To check the accuracy of the wavelength meter we use during SRM certification, we need references with higher accuracy than the transfer standards. We developed a high accuracy reference based on high-resolution spectroscopy of the 780 nm rubidium transition using frequency-doubled light and Doppler-free spectroscopy.⁴ Here's how it works: We stabilize a frequency-doubled 1560 nm laser to a hyperfine component of the rubidium transition and measure the laser's wavelength using a wavelength meter. These measurements verify our wavelength meter's accuracy during SRM certification. We also developed a methane-stabilized source as a high accuracy reference in the 1300 nm region. We stabilized an external-cavity tunable diode laser to the center of a Doppler-broadened methane line and then performed a beat-note measurement

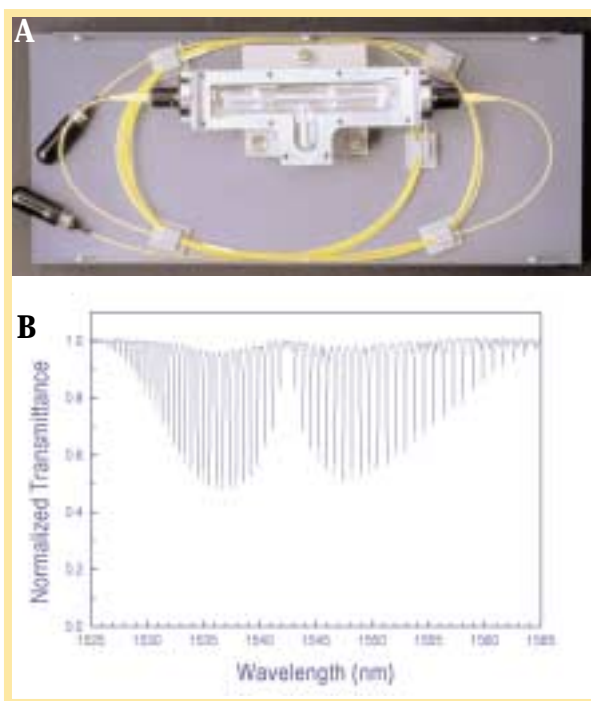
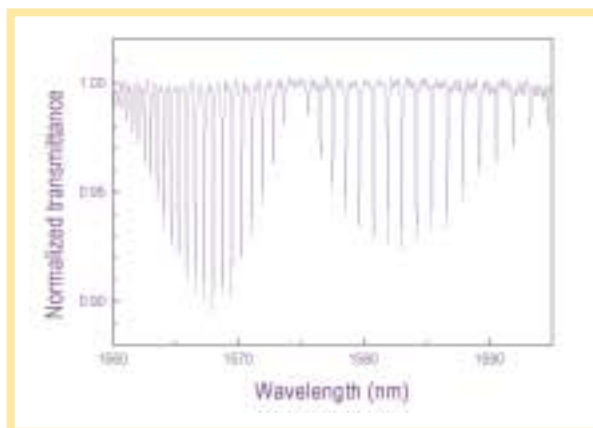


Figure 1. (a) Photo of NIST Standard Reference Material (SRM) 2519, hydrogen cyanide wavelength calibration reference, with the cover removed showing the glass absorption cell. (b) Transmittance spectrum for SRM 2519 ($\text{H}^{13}\text{C}^{14}\text{N}$).

with a calcium frequency standard maintained by NIST. This resulted in the measurement of a methane transition at 1314 nm with an uncertainty of less than 5 MHz (0.03 pm). This methane-stabilized laser now serves as a NIST internal reference to check the accuracy of our wavelength meter in the 1300 nm region.

Figure 2. Transmittance spectrum for carbon monoxide $^{12}\text{C}^{16}\text{O}$, a wavelength calibration reference for the WDM L-band.



After examining a number of molecules as potential references in the new WDM L-band (approximately 1565–1625 nm), we concluded that carbon monoxide is the best candidate for an SRM. The carbon 12 isotope ($^{12}\text{C}^{16}\text{O}$) provides about 40 lines between 1560 and 1595 nm (see Fig. 2), and $^{13}\text{C}^{16}\text{O}$ has about 35 lines between 1595 and 1628 nm.⁵ While these lines are weaker than the absorption lines in either acetylene or hydrogen cyanide, they are strong enough to be considered for a portable wavelength calibration device. We have built a prototype wavelength SRM device and are now investigating the pressure shift and other properties.

But WDM will likely expand into the 1300 and 1400 nm regions—and it will be tough to find absolute references for this wide wavelength range. Calibrated artifact references, such as etalons⁶ or fiber Bragg gratings,⁷ are being investigated. Artifacts can provide references at arbitrary wavelengths. The drawback, however, is that they suffer from sensitivity to temperature, strain, and pressure. Passive or active thermal stabilization can substantially reduce this variability, and the artifacts can be referenced to atomic or molecular standards.^{6,7} Although these references will not be as accurate or stable as the molecular references, they could be implemented in any wavelength region.

Spectral measurements and polarization-dependent loss

The spectral dependence of components is critical in a WDM system. Wavelength channel filters must stay aligned with the International Telecommunication Union (ITU) grid of wavelength channels. Systems typically specify that crosstalk between channels must be less than 25 dB.

NIST's spectral measurement system is directly tied to the wavelength references discussed above. We use the calibrated wavelength meter and a tunable diode laser source to measure the transmittance and reflectance of WDM components. Diode lasers have broadband amplified spontaneous emission (ASE), which will limit the dynamic range of a

measurement system unless a filtered detector or a tunable filter is used to remove it. Adding a tunable fiber Fabry-Perot filter to our system to remove the majority of this ASE emission increased our dynamic range from 23 dB to 64 dB.

We conducted a round robin measurement intercomparison with other organizations and industry participants to assess the current measurement capabilities for wavelength filters.⁸ Participants were given a fiber Bragg grating WDM channel filter, which had both active and passive temperature control, to measure the reflectance and transmittance of the grating as a function of wavelength. The WDM channel filter was also periodically measured at NIST using the system described above. Results: The round robin showed that there are problems with bandwidth and minimum transmittance measurement methods. Measured bandwidth values varied by about 10 GHz—a sizable fraction of the device's 50 GHz bandwidth. Also, most of the participants' minimum transmittance values were about 6 dB above the value measured by NIST, due to inadequate filtering of source ASE spectral noise. Data analysis methods developed by NIST during this study have now been incorporated into a draft Telecommunications Industry Association (TIA) standard test procedure document. NIST plans to continue working with the TIA to develop standard test procedures and evaluate measurement capabilities.

Polarization-dependent loss (PDL)—the variation in transmittance for different polarization states—is an important consideration in both digital and analog networks due to increases in the bit-error-rate and signal distortion. Polarization-dependent loss is defined as $10\log(T_{\max}/T_{\min})$ (in dB), where T is transmittance taken over the entire polarization-state space. PDL is usually characterized as a localized component effect, as opposed to the distributed nature of polarization-mode dispersion (discussed below). The push toward all-optical networks has increased pressure to reduce component PDL. With the implementation of WDM, the wavelength dependence of PDL has assumed greater importance.

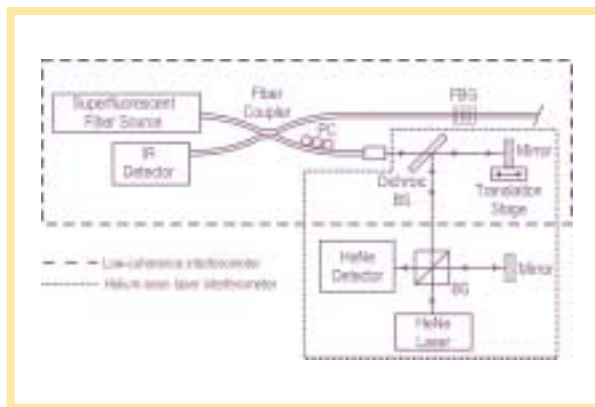
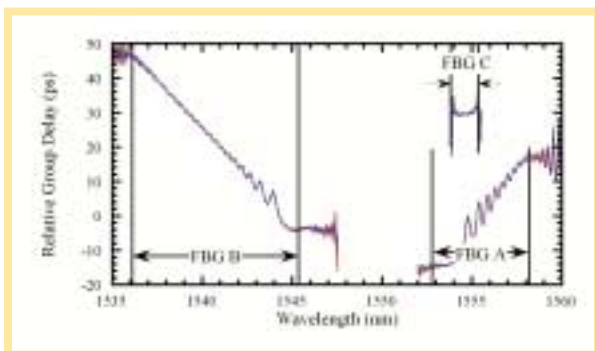


Figure 3. Low-coherence interferometer system with a fiber Bragg grating (FBG) in the test arm (PC = polarization controller; BS = beam splitter). The position of the translating mirror is monitored by a helium-neon laser interferometer.

Our measurement system for the characterization of PDL uses liquid-crystal variable retarders to generate four specific polarization states.⁹ Polarization-dependent loss can be derived from the relative transmittances of the four polarization states. The system is capable of better than 0.001 dB PDL resolution and we have recently extended it to include the measurement of the wavelength dependence of PDL. NIST SRM 2537 is under development for the calibration of PDL measurement instruments. A short section of polarizing fiber produces the PDL, which has a nominal value of 0.1 dB for the length of polarizing fiber used. The polarizing fiber is fusion-spliced between a single-mode input fiber and multi-mode output fiber. Each SRM will be accurately characterized at NIST and certified versus wavelength

Figure 4. Relative group delay of three fiber Bragg gratings measured simultaneously using the low-coherence interferometer.



with an uncertainty of about 0.01 dB over the region of 1530-1560 nm.

Polarization-dependent wavelength shift of a channel filter can be a serious problem, particularly for some planar devices such as arrayed waveguide gratings with high birefringence. We plan to combine our polarization and spectral measurement capabilities and develop a system to accurately characterize polarization-dependent wavelength shift.

Chromatic dispersion

Chromatic dispersion in optical fiber networks, determined from the derivative of the relative group delay versus wavelength, broadens pulses and limits the system data rate. We have developed two measurement systems for relative group delay; one is based on low-coherence interferometry and the other on the more conventional rf-modulated phase-delay method.

The rf-modulated phase-delay system uses a Mach-Zehnder modulator to modulate the optical intensity of a tunable laser.¹⁰ After traversing the fiber or component under test, the light is detected by a vector voltmeter to measure its relative phase (yielding relative group delay) as a function of wavelength. Our system's group delay resolution is about 0.15 ps, but the 1.9 GHz modulation frequency results in a wavelength resolution of about 30 pm. We are currently upgrading the system for higher stability and wavelength resolution by using a lower modulation frequency and an rf lock-in amplifier. We anticipate that the new system will have a wavelength resolution of approximately 2 pm and a group delay resolution of about 0.5 ps. This will enable accurate measurement of narrow-band dispersion effects such as dispersion ripple in fiber Bragg grating dispersion compensators.

We have developed a new technique based on low-coherence interferometry for the measurement of group delay and chromatic dispersion. Our fiber optic Michelson interferometer is shown in Fig. 3. A broadband-erbium-fiber superfluorescent source provides the input signal; the optical component to be measured is spliced to the test arm of the interferometer. The reference arm includes a translation stage and mirror so

that the total optical path difference can be varied. An interferogram is recorded as the reference-arm mirror is translated; the position of the reference arm mirror is tracked by a frequency-stabilized helium-neon laser interferometer. We take a Fourier transform of the interferogram and separate the result into magnitude and phase. The spectral reflectance can be calculated from the magnitude; group delay and dispersion are calculated from the phase. A key advantage of this measurement is its speed; it is possible to obtain the group delay of multiple components in less than 60 seconds.¹¹ Currently, our relative group delay resolution is about 0.1 ps, and the wavelength resolution is between 1 pm and 10 pm, depending on the number of data points used. Both transmission and reflection group delay can be obtained from a single measurement.¹²

The simultaneous measurement of multiple fiber Bragg gratings is important in telecommunication applications where several gratings are used in series as add-drop multiplexers, and in cases where

gratings are concatenated to achieve desired dispersion characteristics. Unlike conventional dispersion measurement systems, the low-coherence technique can be used to distinguish and measure the dispersion of multiple components in a system, even if the components have overlapping reflection bands. We determined the group delay of individual fiber Bragg gratings from a single measurement of a network containing three gratings (Fig. 4).¹²

We are evaluating the use of a molecular absorption line as a potential dispersion calibration reference. An individual molecular absorption line will have a fixed amount of dispersion that can be predicted from first principles. If this work is successful, our wavelength calibration Standard Reference Materials could also be used to calibrate component measurement systems for chromatic dispersion.

Polarization-mode dispersion

The next significant mechanism for pulse-broadening after compensating for chromatic dispersion in a telecommunication

system is polarization-mode dispersion (PMD). PMD arises in optical fibers and components due to birefringence, which gives the light a polarization-dependent propagation velocity. If the component is non-mode-coupled (no coupling between the birefringent eigenaxes along the length of the fiber or component), an input optical pulse will split into two pulses that are orthogonally polarized along the fast and slow axes of birefringence. These pulses are separated by a time proportional to the product of birefringence and optical path length. This separation time is the differential group delay (DGD) and is only weakly dependent on wavelength or environmental conditions in the non-mode-coupled case.

Typical single-mode telecommunication fiber does not fit the above non-mode-coupled description. The fiber's intrinsic birefringence is so small that it is overwhelmed by the localized stresses occurring during the drawing process and deployment, or by environmental conditions. These stress points induce a local

Higher-resolution copies of the figures are included at the end of the paper

birefringence that couples the eigenmodes of the inherent fiber birefringence. In long fibers with many of these mode-coupling sites, the PMD behavior is significantly more complicated than the non-mode-coupled case. A highly mode-coupled fiber resembles a concatenation of short sections of birefringent fiber with their polarization axes randomly aligned. When the fiber is cabled or moved, or when environmental conditions change, the location and strength of the mode-coupling sites can change, altering the DGD measured at a given wavelength. A more robust metric for this situation is the PMD, which is defined as the statistical mean of the DGD averaged over wavelength.

The methods of measuring PMD can be broken into two general categories: polarimetric techniques capable of measuring instantaneous DGD as a function of wavelength, and non-polarimetric techniques that measure only mean DGD over a broad wavelength range (tens of nanometers). Examples of polarimetric techniques are Jones matrix eigenanalysis, Poincaré arc (also called "state of polarization"), and modulation phase shift techniques. Examples of non-polarimetric techniques are low-coherence interferometry and fixed analyzer (also called "wavelength scanning") techniques. We developed a Jones matrix eigenanalysis measurement system that has a PMD uncertainty of 3.2 fs.¹³

NIST supports PMD metrology through two SRMs. The first is SRM 2518 "Polarization-Mode Dispersion (Mode-Coupled)"¹⁴—an artifact designed to emulate a telecommunication fiber in that the DGD-versus-wavelength characteristics mimic the quasi-random behavior, but without the accompanying environmental instability of fiber. The SRM is a fiber-pigtailed stack of nominally 35 quartz waveplates with randomly oriented birefringence axes (Fig. 5). This device exhibits the characteristic "random-mode-coupled" DGD spectrum with a nominal mean of 0.5 ps (Fig. 6). SRM 2518 is certified (for PMD polarimetric measurement techniques only) with typical uncertainties of 1-2 % over several different wavelength

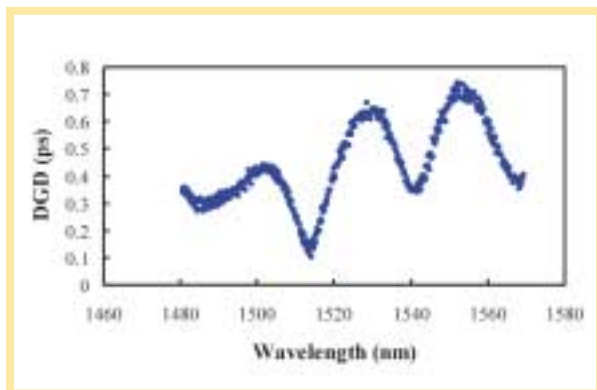


Figure 5. SRM 2518 for polarization-mode dispersion calibration, showing the optical fiber pigtailed quartz waveplate stack.

Figure 6. Typical differential group delay (DGD) spectrum for SRM 2518.

ranges within a 1480-1570 nm window.

The second SRM is being developed to support metrology of components exhibiting no polarization-mode coupling. SRM 2538 "Polarization-Mode Dispersion (Non-Mode-Coupled)" consists of a single quartz waveplate pigtailed with single-mode fiber. The waveplate is held in a temperature-controlled housing and the mean DGD over several wavelength ranges will be certified (for all measurement techniques) to an uncertainty of about 1-2 %.

Summary

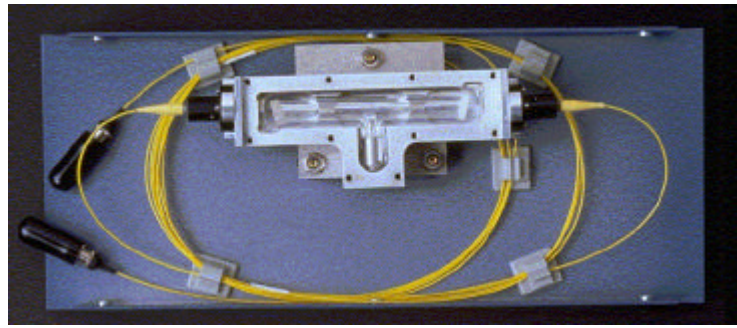
The NIST Optical Components Group develops techniques and standards to support the measurement of optical fiber and components used in dense WDM optical fiber communication systems. We have described our current projects on wavelength calibration transfer standards and the measurement of spectral response, dispersion, and polarization dependence of

optical fiber and components. Future work will include developing wavelength calibration standards outside the 1500 nm region and higher resolution measurement capabilities for dispersion. We also plan to start an effort on the measurement of nonlinear properties of optical fiber.

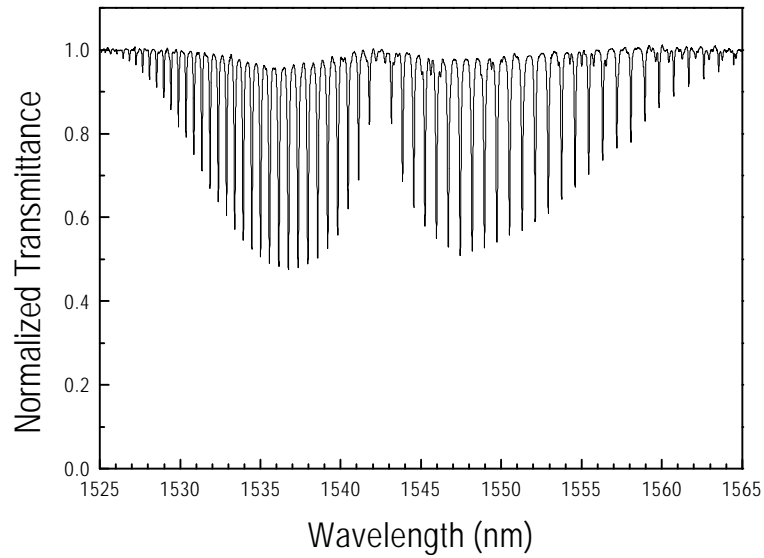
References

1. K. Nakagawa, M. de Labacherie, Y. Awaji, and M. Kourogi, "Accurate optical frequency atlas of the 1.5- μ m bands of acetylene," *J. Opt. Soc. Am. B* **13**, 2708-14 (1996).
2. H. Sasada and K. Yamada, "Calibration lines of HCN in the 1.5- μ m region," *Appl. Opt.* **29**, 3535-47 (1990).
3. W.C. Swann and S.L. Gilbert, "Pressure-induced shift and broadening of 1510-1540-nm acetylene wavelength calibration lines," *J. Opt. Soc. Am. B* **17**, 1263-70 (2000); S.L. Gilbert and W.C. Swann, "Acetylene $^{12}\text{C}_2\text{H}_2$ Absorption Reference for 1510nm to 1540 nm Wavelength Calibration - SRM 2517a," *Natl. Inst. Stand. Technol. Spec. Publ.* 260-133 (2001).
4. S.L. Gilbert, W.C. Swann, and C.M. Wang, "Hydrogen Cyanide $\text{H}^{13}\text{C}^{14}\text{N}$ Absorption Reference for 1530-1560 nm Wavelength Calibration - SRM 2519," *Natl. Inst. Stand. Technol. Spec. Publ.* 260-137 (1998).
5. L.S. Rothman *et al.*, "The Hitran molecular database: editions of 1991 and 1992," *J. Quant. Spectrosc. Rad. Transf.* **48**, 469-507 (1992).
6. D.A. Humphreys, "Accurate wavelength calibration for optical spectrum analyzers," in *Technical Digest - Symposium on Optical Fiber Measurements*, *Natl. Inst. Stand. Technol. Spec. Publ.* 905, 97-100 (1996).
7. W.C. Swann, M.A. Hubbard, and S.L. Gilbert, "Hybrid multiple wavelength reference using fiber gratings and molecular absorption," in *Proc., Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides*, *OSA Technical Digest (Optical Society of America, Washington DC, 1999)*, 63-5.
8. A. H. Rose, C.-M. Wang, and S. D. Dyer, "Optical Fiber Bragg Grating Metrology Round Robin," *J. Res. Natl. Inst. Stand. Technol.*, **105**, (2000), In Press.
9. R. Craig, S. L. Gilbert and P. D. Hale, "High Resolution, Nonmechanical Approach to Polarization Dependent Transmission Measurements," *IEEE J. Light-wave Technol.* **16**, 1285-94 (1998).
10. S. E. Mechels, J. B. Schlager, and D. L. Franzen, "Accurate measurements of the zero-dispersion wavelength in optical fibers," *J. Res. Natl. Inst. Stand. Technol.* **102** (3), 333-47 (1997).
11. S. D. Dyer, K. B. Rochford, and A. H. Rose, "Fast and accurate low-coherence interferometric measurements of fiber Bragg grating dispersion and reflectance," *Optics Express* **5**, 262-6 (1999).
12. S. D. Dyer and K. B. Rochford, "Low-coherence interferometric measurements of the dispersion of multiple fiber Bragg gratings," accepted for publication in *IEEE Photon. Technol. Lett.*
13. P.A. Williams, "Rotating-wave-plate Stokes polarimeter for differential group delay measurements of polarization-mode dispersion," *Appl. Opt.* **38**, 6508-15 (1999).
14. P.A. Williams, "Mode-coupled artifact standard for polarization-mode dispersion: Design, assembly, and implementation," *Appl. Opt.* **38**, 6498-507 (1999).

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(a)



(b)

Figure 1. (a) Photo of NIST Standard Reference Material (SRM) 2519, hydrogen cyanide wavelength calibration reference, with the cover removed showing the glass absorption cell. (b) Transmittance spectrum for SRM 2519 ($\text{H}^{13}\text{C}^{14}\text{N}$).

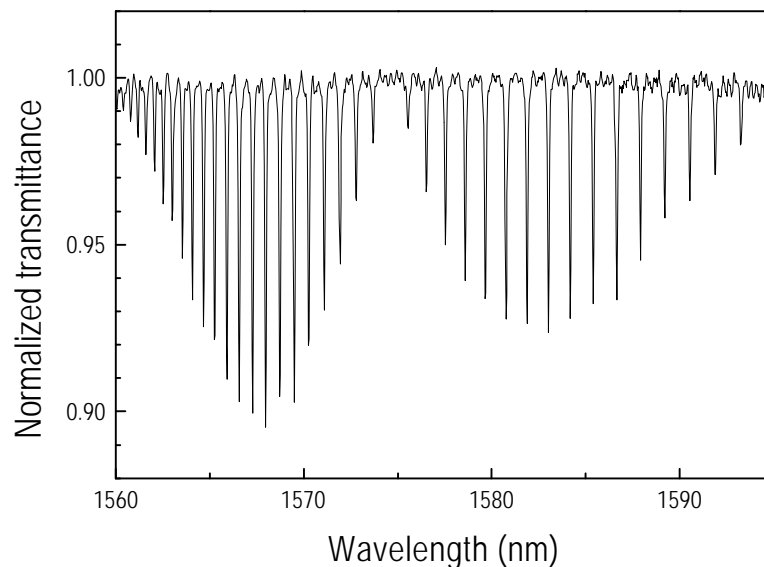


Figure 2. Transmittance spectrum for carbon monoxide $^{12}\text{C}^{16}\text{O}$, a wavelength calibration reference for the WDM L-band.

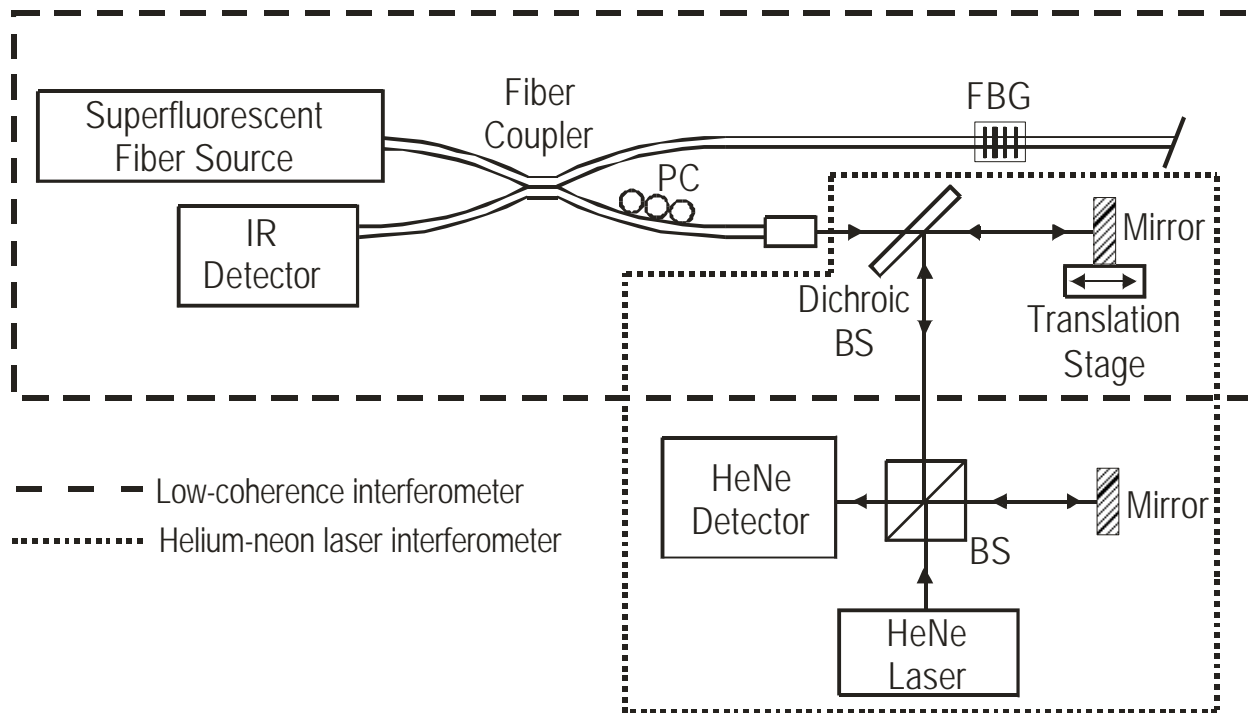


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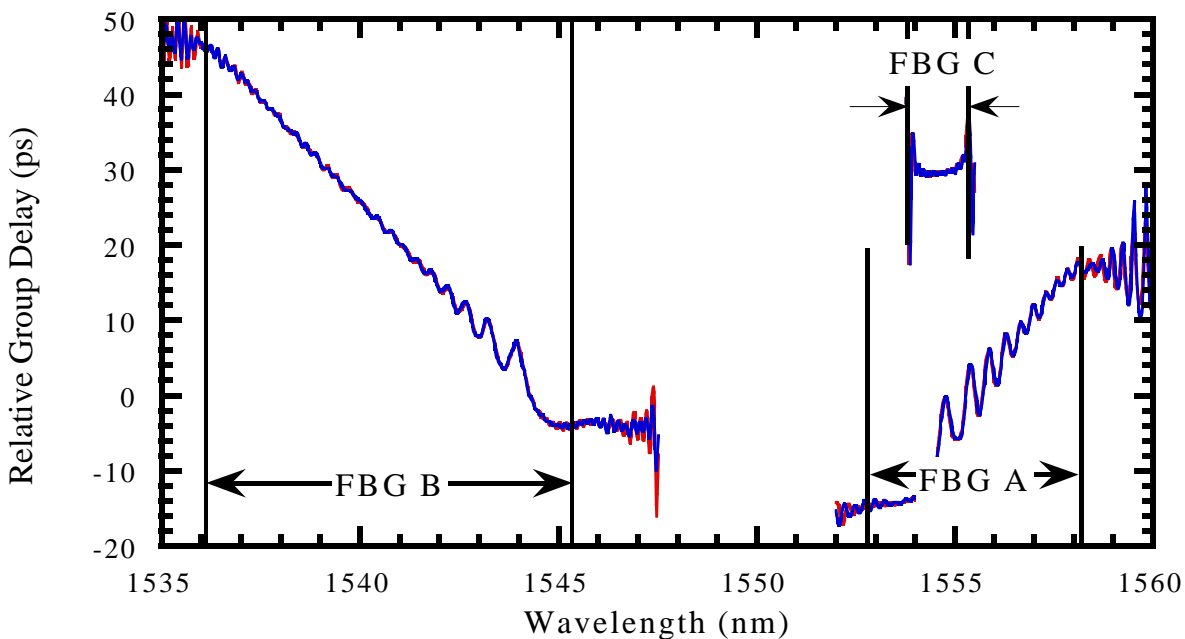


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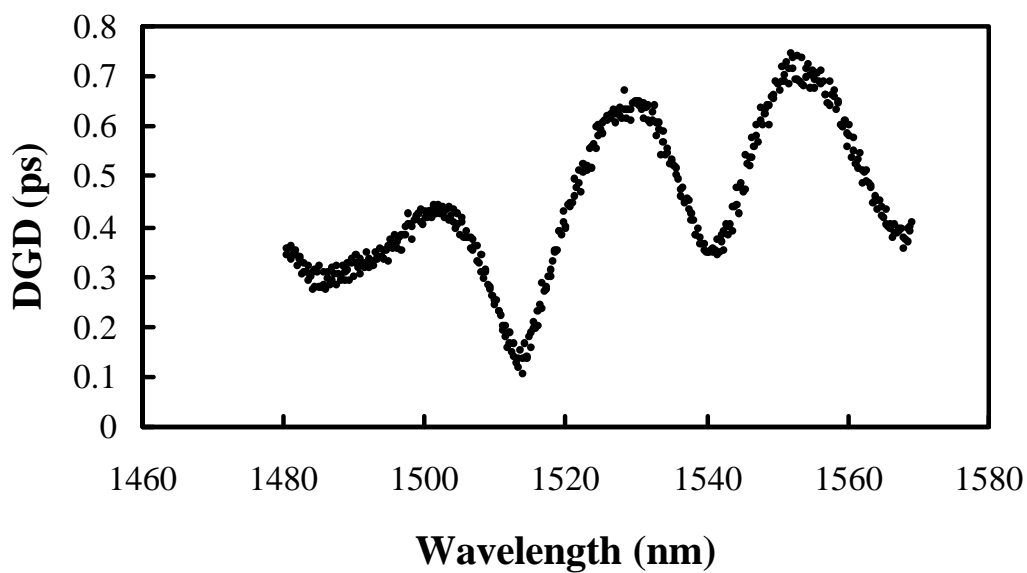


Figure 6. Typical differential group delay (DGD) spectrum for SRM 2518.